Polarization-mode dispersion measurement using a six-state RF phase-shift technique for high spectral efficiency

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Abstract: We demonstrate record spectral efficiency for RF phase-shift measurement of differential group delay and principal states of polarization. Unaveraged uncertainty is below 40 fs in 4.92 GHz bandwidth. Uncertainties and measurement procedures are detailed.

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1. Introduction

As a dispersive effect, the measurement of polarization-mode dispersion (PMD) requires a finite optical bandwidth. This leads to a reciprocal relationship between temporal uncertainty and measurement bandwidth. However, in measuring the PMD of wavelength-division multiplexed components, it is important to be able to measure with both low temporal uncertainty and high spectral resolution (small measurement bandwidth). Recently, techniques have been developed to efficiently measure differential group delay (DGD) in a narrow spectral bandwidth. Two major approaches are techniques based on radio-frequency (RF) phase-shift [1, 2], and swept-wavelength interferometry [3]. We have assembled an RF modulation phase-shift (MPS) technique with the goal of optimizing and rigorously quantifying the spectral efficiency. We describe results that we believe to be the state of the art in spectral efficiency for PMD measurements, as well as some best practices to reduce uncertainty in narrowband PMD measurement.

2. Measurement description

The measurement setup shown in Figure 1 is similar to the design of Reference [1]. We launch known polarization states of RF-modulated light into the device under test (DUT) and measure the resulting RF phase of the light at the detector. Since RF phase at the detector depends on the group delay through the DUT, varying the launched polarization state will allow the polarization dependence of the group delay through the device to be measured, yielding both the DGD and the principal states of polarization (PSP).

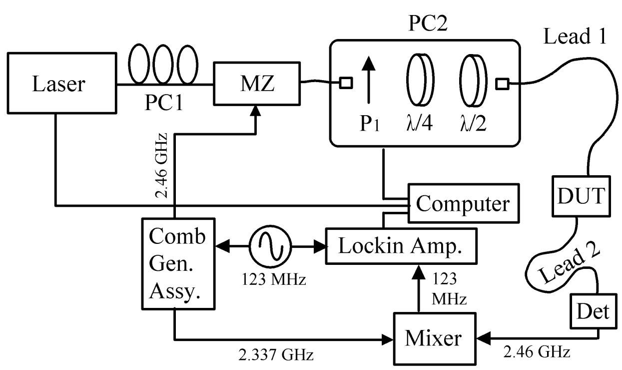

Fig. 1. MPS system: polarization controls (PC1, PC2), Mach-Zehnder modulator (MZ), Comb Generator Assembly (yields harmonics of 123 MHz), polarizer (P1), waveplates (λ/4, λ/2), device under test (DUT), and detector (Det).

Specifically, a tunable laser is amplitude-modulated at 2.46 GHz by means of a Mach-Zehnder modulator (passively biased at quadrature). The polarization state of the light is deterministically controlled by the polarization controller (PC2). The light passes through the DUT and is detected with a detector of 7 GHz bandwidth. A lockin amplifier measures the RF phase of the detected signal referenced to the electrical signal driving the modulator. The measured RF phase for four appropriately chosen polarization states is sufficient to determine both the DGD and the PSP [1,2]. However, we reduce drift and measurement noise by launching a set of six "mutually orthogonal" polarization states (four states evenly spaced on a great circle of the Poincaré sphere and two states on the axis of that circle). The absolute orientation of these six states has no bearing on the measured DGD (provided they remain mutually orthogonal to each other), but defines the basis vector set to which the direction of the PSPs are referenced.

As described in Reference [1], a polarization state launched into the DUT produces a total RF phase

$$\phi_{Tot,S_i} = \phi_{S_i} + \Phi \quad (1)$$

at the lockin amplifier. The subscript S_i represents a particular launched polarization state, and ϕ_{S_i} and Φ respectively are the polarization-dependent and polarization-independent delays. Polarization states separated by 180º on the Poincaré sphere (denoted by the subscripts S_i and S_{-i}) yield RF phases with equal values of Φ and equal and opposite values of ϕ_{S_i}. So, the polarization-dependent RF phase for a launch state S_i is found as

$$\phi_{S_i} = \frac{(\phi_{Tot,S_i} - \phi_{Tot,S_{-i}})}{2}. \quad (2)$$

The DGD of the DUT can be determined from this polarization-dependent RF phase from three "mutually orthogonal" (each 90º away from the others on the Poincaré sphere) polarization states $\boldsymbol{S_A}$, $\boldsymbol{S_B}$, and $\boldsymbol{S_C}$. These states are defined (in terms of the reduced Stokes vectors) as any triad of states such that

$$\boldsymbol{S_A} = \boldsymbol{R}\cdot\begin{pmatrix}1\\0\\0\end{pmatrix},\quad \boldsymbol{S_B} = \boldsymbol{R}\cdot\begin{pmatrix}0\\1\\0\end{pmatrix},\quad \boldsymbol{S_C} = \boldsymbol{R}\cdot\begin{pmatrix}0\\0\\1\end{pmatrix},\quad \boldsymbol{S_{-A}} = -\boldsymbol{S_A},\quad \boldsymbol{S_{-B}} = -\boldsymbol{S_B},\quad \boldsymbol{S_{-C}} = -\boldsymbol{S}_C, \quad (3)$$

where $\boldsymbol{R}$ is a rotation matrix made up of an arbitrary number of rigid rotations in Stokes space. We measure the polarization-dependent phase by launching the state pairs $\boldsymbol{S_A}$, $\boldsymbol{S_{-A}}$; $\boldsymbol{S_B}$, $\boldsymbol{S_{-B}}$; and $\boldsymbol{S_C}$, $\boldsymbol{S_{-C}}$ and using Equation (2). The measured DGD is independent of $\boldsymbol{R}$ and given as

$$\Delta\tau = \frac{1}{\pi f}\tan^{-1}\left[(\tan^2\phi_{S_A} + \tan^2\phi_{S_B} + \tan^2\phi_{S_C})^{1/2}\right]. \quad (4)$$

The polarization dispersion vector Ω is the PSP vector with a magnitude equal to the DGD and is given by

$$\boldsymbol{\Omega} = \frac{\Delta\tau}{\tan(\Delta\tau\,\pi f)}\boldsymbol{R^{-1}}\cdot\begin{pmatrix}\tan(\Delta\phi_{RF,S_A})\\ \tan(\Delta\phi_{RF,S_B})\\ \tan(\Delta\phi_{RF,S_C})\end{pmatrix}, \quad (5)$$

where $\boldsymbol{R^{-1}}$ is the inverse of $\boldsymbol{R}$.

3. Measurement uncertainty

Low measurement uncertainty requires accurate equipment and proper technique. We detail aspects of both below.

We find 10 fs to be the practical lower limit of measurable DGD. Below this value, the bias due to internal DGD (polarization-dependent group delay internal to our measurement system) dominates. The upper limit comes from a 180° phase ambiguity at the lockin amplifier, which, for our 2.46 GHz modulation frequency occurs above 203 ps.

Our modulator operates at 2.46 GHz with the detected signal mixed down to 123 MHz to be readable by the lockin amplifier. Under these conditions, the lockin's 0.02° phase resolution predicts a temporal resolution of 22.6 fs. We selected amplifier components based on low noise-figure specifications, and minimize reflections by carefully cleaning each RF and optical connector and using a torque wrench on RF connections. Shielding the detector in aluminum foil was necessary to reduce coherent pickup to below -50 dB.

Our measurement system has four internal sources of DGD: the polarization controller PC2 (9 fs), the fiber leads (two leads with 0.8 fs each), and the detector (11 fs). In the presence of internal DGD, the lowest uncertainty is achieved by randomizing the orientations of these components with respect to each other between measurements and averaging the results. So, we physically re-orient the fiber leads between measurements, and randomly change the absolute orientation of the six launched polarization states (randomizing $\boldsymbol{R}$ in Equation (3)). This randomizes the alignment of the PSP axes of the various internal DGDs so when the value of the DUT is larger than the internal DGD, multiple measurements yield a negligible measurement bias (MPS result - true DGD). Figure 2 shows the expected bias and standard deviation of measured DGD as a function of true DGD with the internal DGD values mentioned above. Simulation with the concatenation rules of Reference [4] shows that the internal DGD contribution to the standard deviation of the mean for multiple measurements varies as $N_F^{-1/2}$, where N_F is the number of statistically independent measurements (measured with the fiber leads reoriented and $\boldsymbol{R}$ randomized).

Drift in the DUT can be a significant source of uncertainty. Since RF phase shift is a differential time-of-flight measurement, drift in the optical path length causes the DGD to be measured as the difference of large noisy numbers. The mitigations for this drift are to temperature-stabilize the DUT and measurement system as much as possible and to sample quickly. We measure RF phase for pairs of launched polarization states S_i and S_{-i}. Most of the thermal drift comes from the polarization-independent term Φ of Equation (1), so, to find ϕ_{S_i}, we measure RF phase in the sequence ϕ_{Tot,S_i}, $\phi_{Tot,S_{-i}}$, ϕ_{Tot,S_i}. Averaging the first and second measurement of ϕ_{Tot,S_i} and using it in Equation (2) allows the correct value of the polarization-dependent phase ϕ_{S_i} to be found even if there is a linear drift in the group delay over the 4.3 s sampling time.

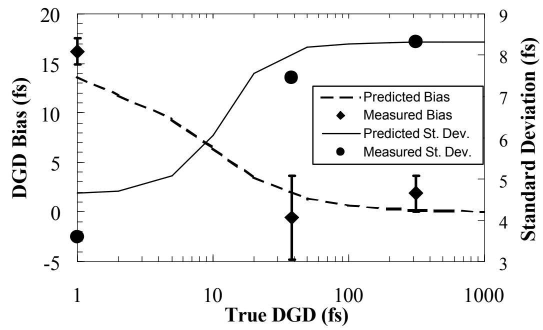

Fig. 2. MPS bias and standard deviation versus true DGD. Error bars are two standard deviations of the mean of multiple measurements. To allow log scale plotting, points for no DUT (zero DGD) are plotted with a "True DGD" value of 1 fs.

We estimate DGD measurement linearity by measuring a PMD emulator that generates known DGD values from 0.5 ps to 100 ps. MPS results agree with the emulator within the 1.5 % uncertainty of the emulator. This is the dominant source of our MPS uncertainty; it can likely be improved.

The expanded uncertainty (~ 95 % confidence interval [5]) of the measurement is given as

$$U = 2u_{Tot} = 2\sqrt{\left(\frac{79.4}{\Delta\tau_{DUT}}\right)^2 + \left(\frac{\sigma_{Int}}{\sqrt{N_F}}\right)^2 + \left(\frac{\sigma_{phase}}{\sqrt{N_{Tot}}}\right)^2 + (\eta\Delta\tau_{DUT})^2}, \qquad (6)$$

where the terms under the radical are (left to right) internal DGD bias, random internal DGD (σ_{Int} = 8.3 fs), phase noise (σ_{phase} = 8.9 fs, N_{Tot} = total number of measurements), and calibration uncertainty (η = 0.015). $\Delta\tau_{DUT}$ is the true DGD of the DUT (in femtoseconds). If multiple measurements are impractical, Equation (6) predicts the single-measurement uncertainty (for DUTs in the range of 10 fs to 1000 fs) to be less than 40 fs with a ~ 95 % confidence interval.

To verify our uncertainty estimate, we measured three cases (no DUT, a 38.2 fs artifact and a 315 fs artifact), all non-mode-coupled. The true DGD of these artifacts is known from Jones matrix eigenanalysis (JME) measurements. The difference with our MPS results yield the bias (MPS result – JME result) and standard deviation for multiple measurements. For each artifact, we made at least 21 independent measurements. The measured bias and standard deviation are shown as points in Figure 2. The 38.2 fs and 315 fs artifacts yielded biases less than 2 fs. Error bars on the experimental points represent two standard deviations of the mean from repeated measurements.

4. Conclusions

We have demonstrated a 4.92 GHz bandwidth MPS measurement with < 40 fs single-measurement expanded uncertainty for DGDs between 10 and 1000 fs. We have also shown that averaged measurements of DGD values less than 0.5 ps agree within 2 fs of the true values. As the mean DGD grows beyond 1000 fs, the uncertainty source will be dominated by the linearity term; better emulator calibration could improve this.

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